What the #$*! Do We (K)now!? about Quantum Mechanics

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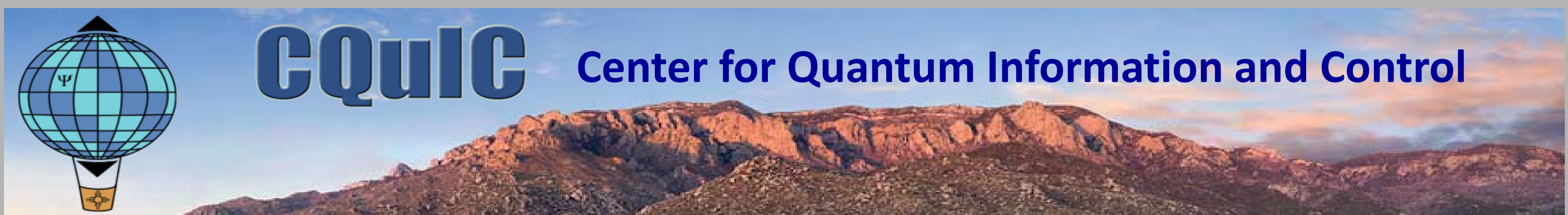

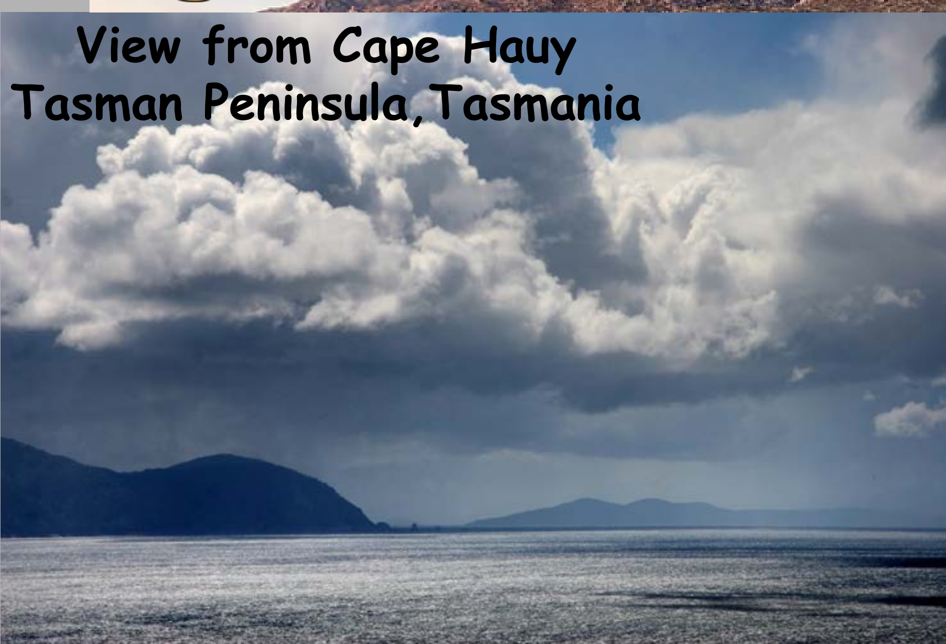

View from Cape Hauy
Tasman Peninsula, Tasmania

Aspens in the Sangre de Cristo Range
Northern New Mexico

There is magic in the world of the very small.

And that magic is described by quantum mechanics.

Quantum mechanics governs the behavior of the very small, but how small are we talking about?

1 meter	m	human height
10^{-3} meter	millimeter (mm)	human hair
		size of eukaryotic plant cell
		size of eukaryotic animal cell
10^{-6} meter	micrometer (µm)	size of Escherichia coli
		wavelength of visible light
		thickness of cell membrane
10^{-9} meter	nanometer (nm)	size of amino acid, X-ray wavelength
		size of an atom
10^{-12} meter	picometer (pm)	gamma-ray wavelength
10^{-15} meter	femtometer (fm)	size of atomic nucleus

What's strange about the behavior of quantum systems?

Waves vs. particles

Indeterminacy

Uncertainty principle

$$h = 6.6261 \times 10^{-34}\,\text{joule-sec}$$

Complementarity

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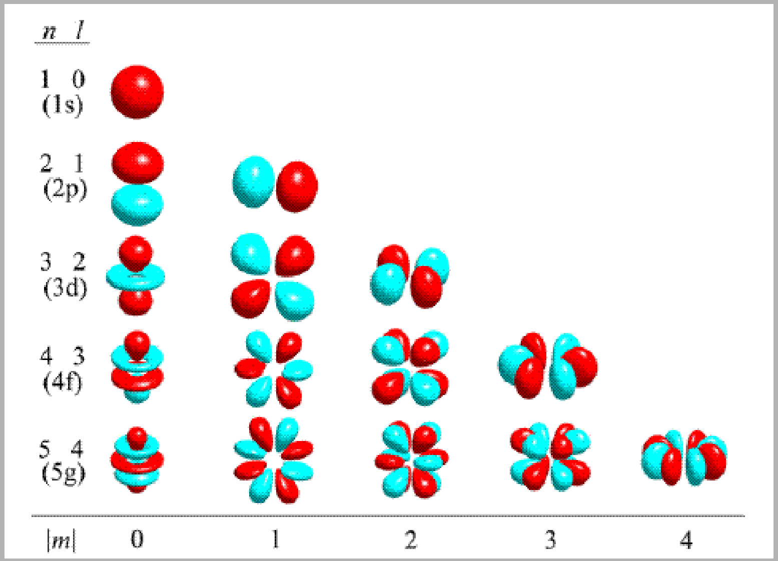
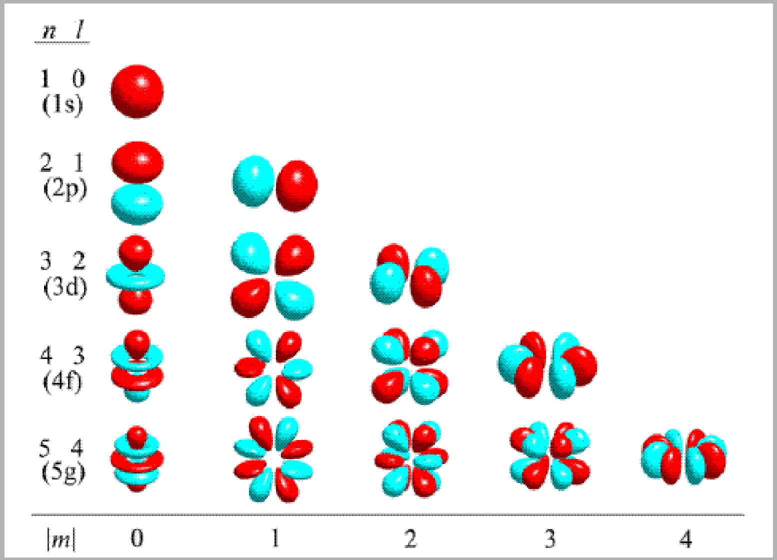
Complementarity



What’s strange about the behavior of quantum systems?

$$h = 6.6261 \times 10^{-34} \text{ joule-sec}$$



Max Planck
(1858-1947)

Niels Bohr
(1885-1962)

Given a proton and an electron, balancing the electron’s (positive) energy of motion with its (negative) electrical binding energy, within the constraints of the uncertainty principle, determines the size of an atom to be about 0.1 nanometer. Putting the mass of the proton in each volume of this size gives the density of ordinary matter.

What's strange about the behavior of quantum systems?

Entanglement
Quantum correlations

"Great! But I might be more impressed if I had a clue what a correlation is, much less a quantum correlation."

Erwin Schrödinger
(1881-1961)

John S. Bell
(1928-1990)

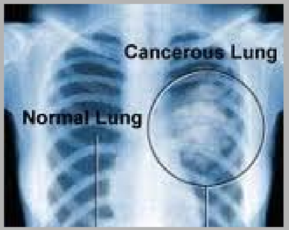
N. David Mermin
(1935-)


Cable Beach
Western Australia
Get ready! I'm going to try to explain why entanglement is weird, but we'll need a major detour to get there.

Correlations

Student at Harvard University

Lung cancer



Smoking

Politically left

Drinking lattes

Good teeth

Perfect correlation

Left foot		Right foot
Cowboy boot		Cowboy boot
Sandal		Sandal
Biking shoe		Biking shoe
Ski boot		Ski boot

A correlation is an association between things. It's perfect when the association always occurs.

Oljeto Wash
Southern Utah

A correlation game

Sacagawea was a Lemhi Shoshone woman, who accompanied the Lewis and Clark Expedition, acting as an interpreter and guide, in their exploration of the Western United States. She traveled thousands of miles from North Dakota to the Pacific Ocean between 1804 and 1806.

Sculpture, in Bismarck, North Dakota,of Sacagawea and her baby, Jean-Baptiste Charbonneau.

Sacagawea 1US$ coin

Heads		Tails
0	Bit	1
Up		Down

The face on the coin was modeled on a Shoshone-Bannock woman named Randy'L He-dow Teton, then a student at the University of New Mexico.

A correlation game

Correlations between coins held by Alice and Bob can be used to “teleport” the state of Victor’s coin to Bob.

Sacagawea 1US$ coin

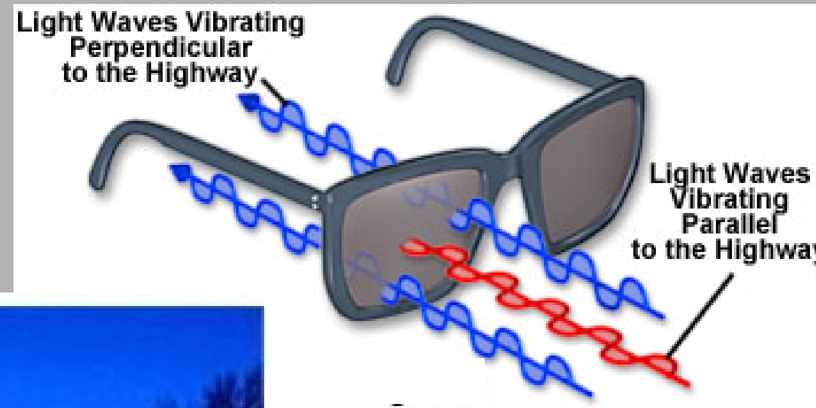
Heads		Tails
0	Bit	1
Up		Down

1. Alice only needs to know that her and Bob’s coins are correlated, not whether they are both heads or both tails.
2. Alice doesn’t need to determine whether Victor’s coin is heads or tails.
3. The message she sends to Bob doesn’t reveal whether Victor’s coin is heads or tails.

Correlations can be used to send information without actually sending it.

Echidna Gorge
Bungle Bungle Range
Purnululu National Park
Western Australia

Polarization of light



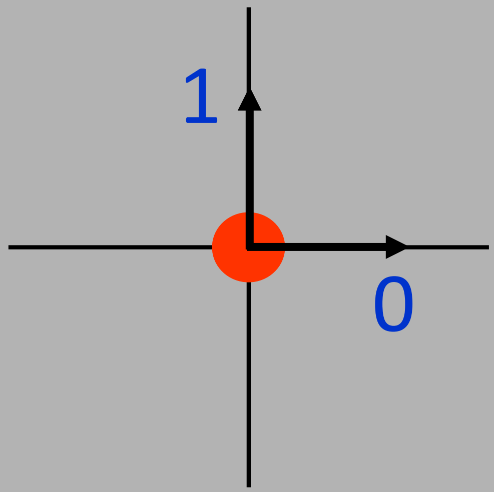
No polarized glasses

Polarized glasses

A source of
polarized light

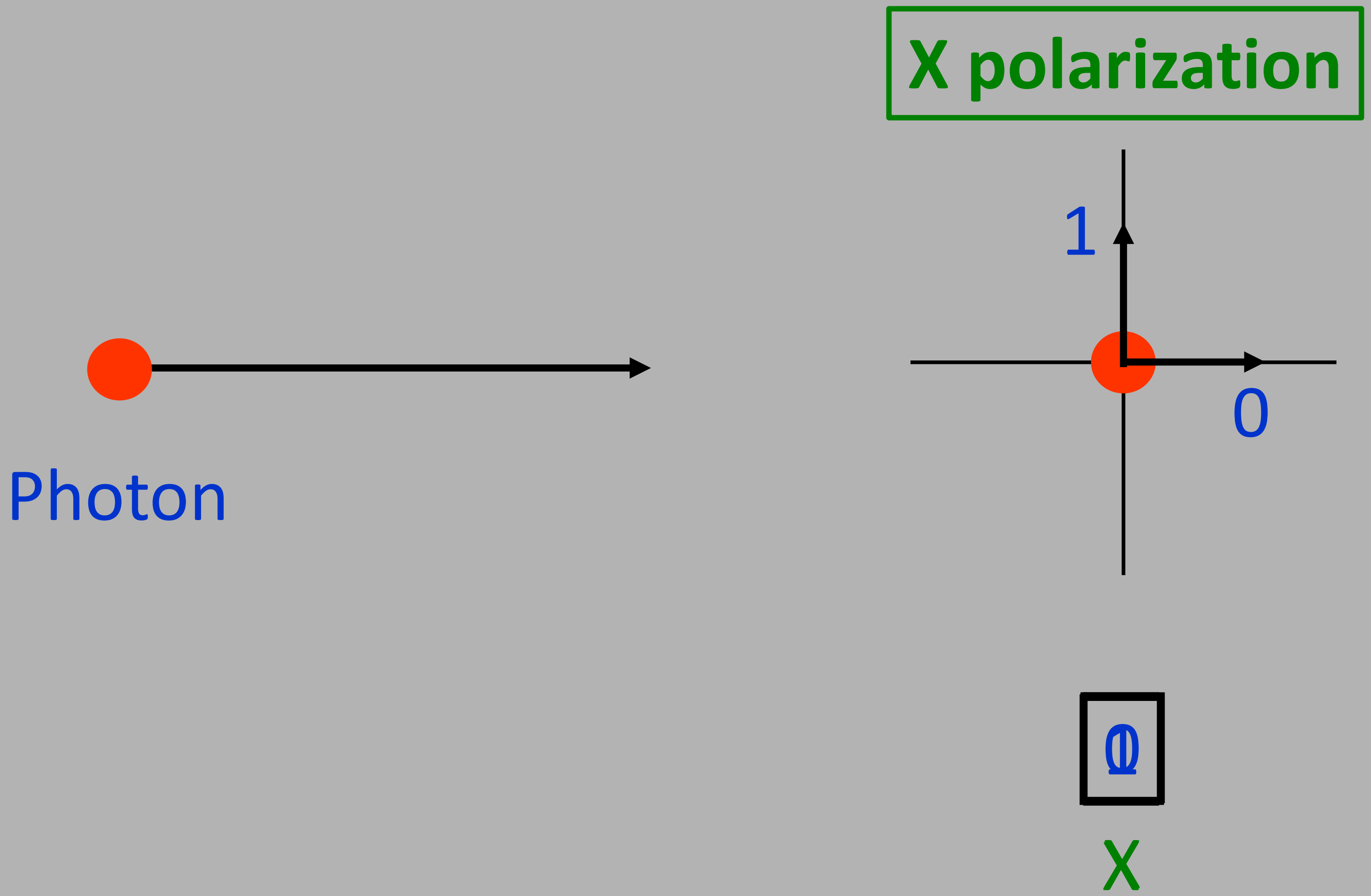
Polarization of a single photon (particle of light)

Photon



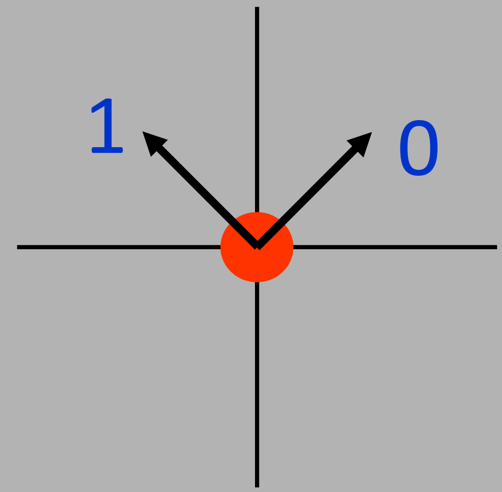
Photon polarization

Photon polarization

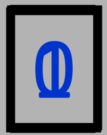


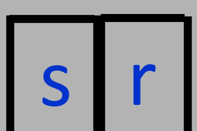
Photon polarization

Y polarization



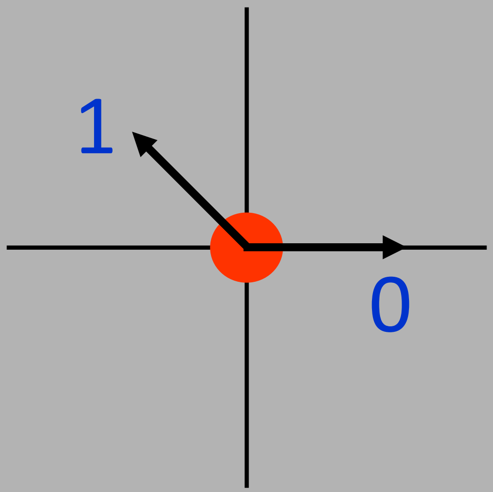
Quantum coin
Two-state quantum system
Qubit





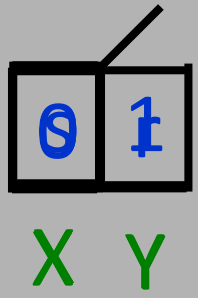
Quantum coin
Photon polarization
Qubit

Photon



Quantum rules

1. Only one polarization at a time can be prepared or measured.
2. When one polarization is measured, the other is randomized.



Classical bit vs. qubit

A classical bit is either on or off.

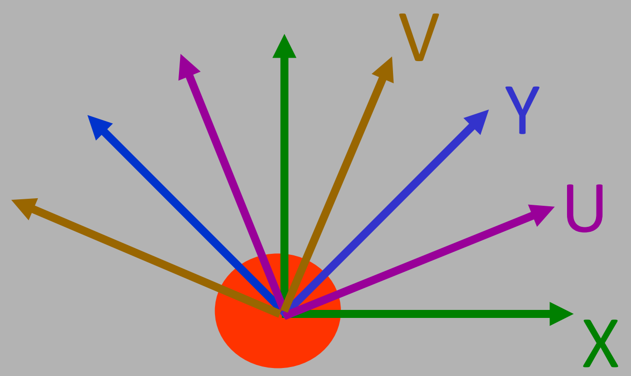
A few electrons on a capacitor

A pit on a compact disk

A 0 or 1 on the printed page

A smoke signal rising from a distant mesa

A qubit has a continuum of on-off properties.



continuum of one-bit coins
(linear polarizations)

A *quantum state* tells you the odds for getting 0 or 1 when you examine any of these one-bit coins (linear polarizations).

What happened to Planck's constant?

Max Planck (1858-1947)

Planck initiated the study of quantum mechanics when he announced in 1900 the results of his theoretical research into the radiation and absorption of a "black body."

$$h = 6.6261 \times 10^{-34} \text{ Joule-sec}$$

Planck's constant is the scale on which physical phenomena are discrete (or grainy); for example, photons are the expression of the discreteness of the electromagnetic field.

World of classical physics

World of quantum physics

Continuous, smooth (analogue)

I don’t care if you are at Hogwarts, Harry. You can’t violate the uncertainty principle.

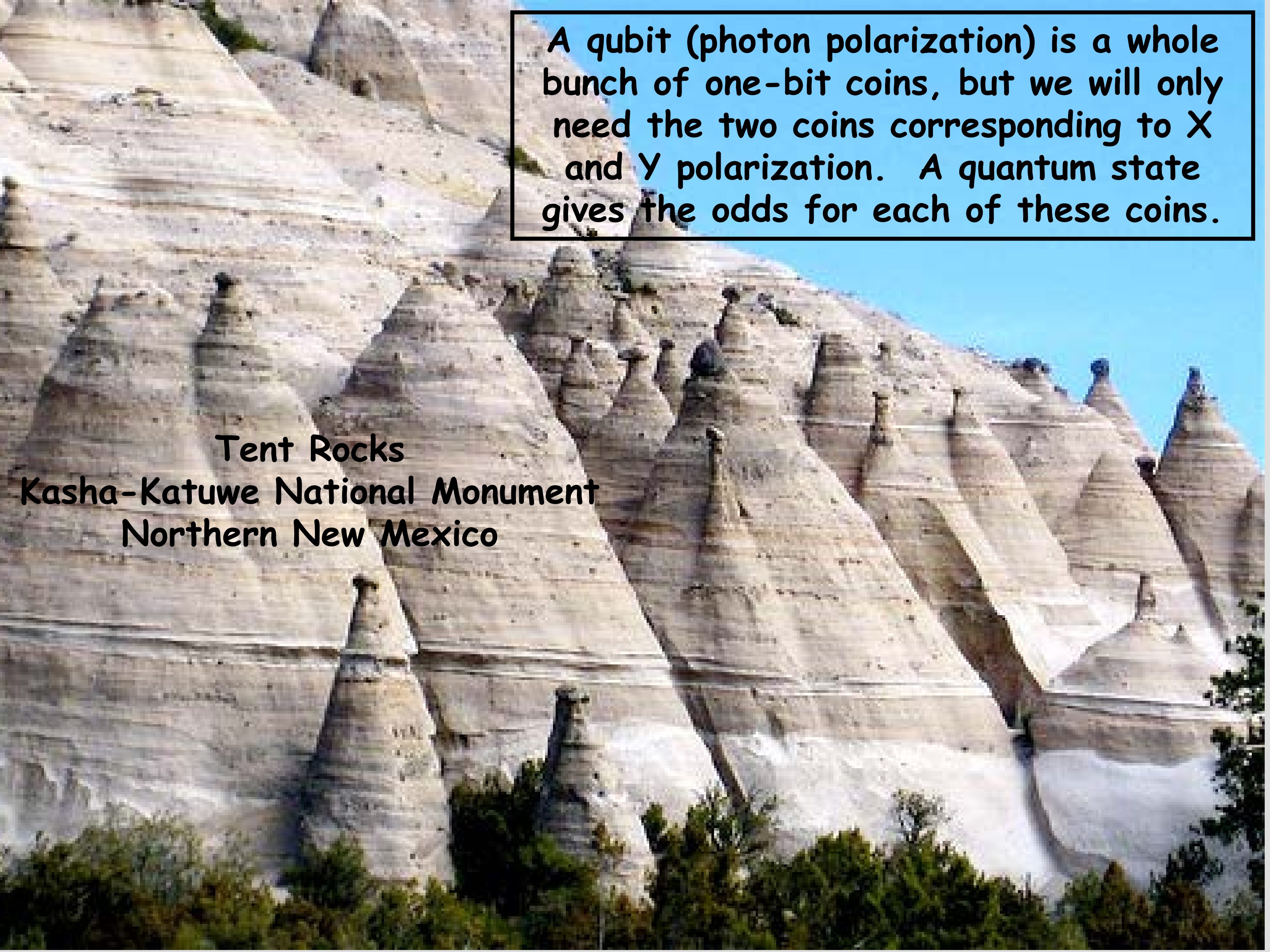
Discrete, grainy (digital)

Information-processing perspective

Use your quantum mechanics, Harry. Feel the quantum reality.

Digital devices (on-off)

Continuum of digital properties

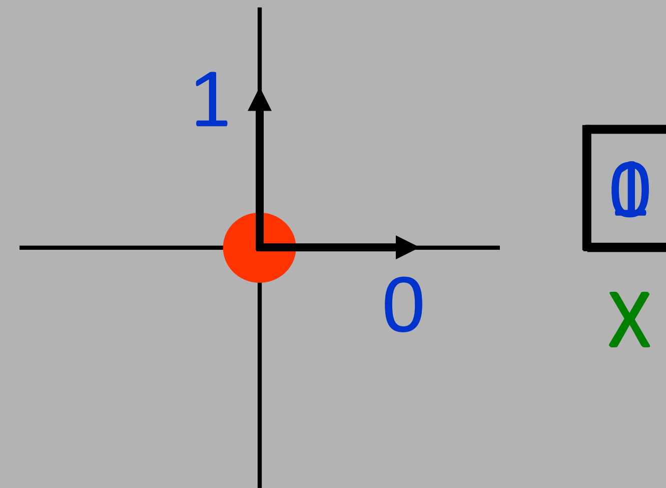

A qubit (photon polarization) is a whole bunch of one-bit coins, but we will only need the two coins corresponding to X and Y polarization. A quantum state gives the odds for each of these coins.
Tent Rocks
Kasha-Katuwe National Monument
Northern New Mexico

Entanglement (at last): quantum correlations

Perfect correlation, with the two results, 00 or 11, being equally likely.


Alice

Photon A



Parametric downconverter

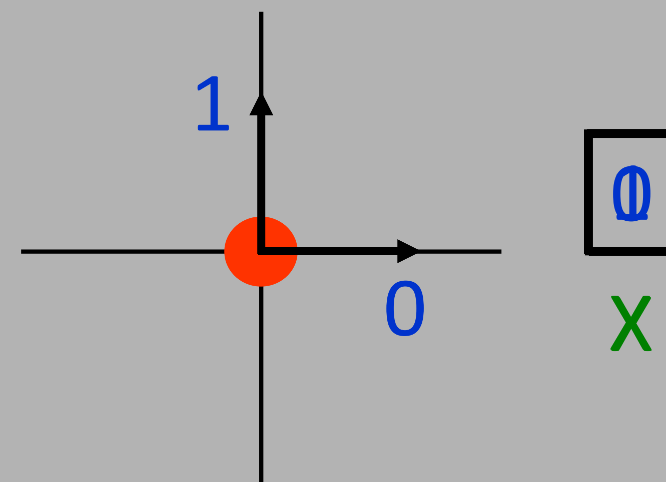
Bell entangled quantum state

$$\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

X polarization


Bob

Photon B

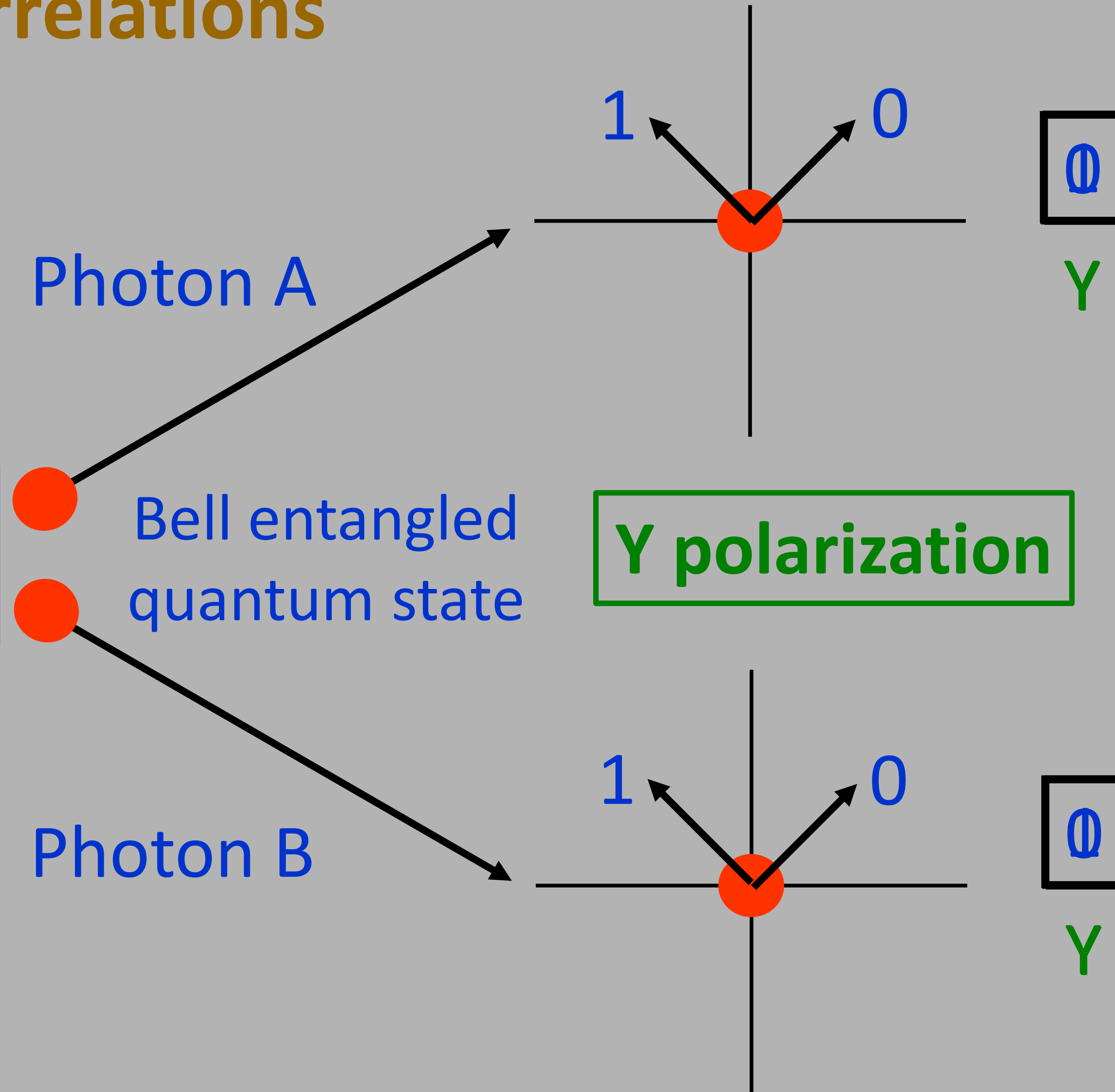


Entanglement (at last): quantum correlations

Perfect correlation, with the two results, 00 or 11, being equally likely.

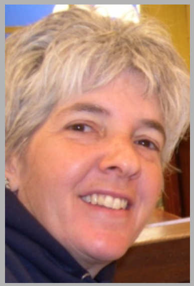
Alice

Parametric downconverter



Bob

A quantum correlation game: Quantum teleportation



Victor

Photon V

Alice

Photon A

Bell entangled quantum state

Photon B

Bob

Alice makes a special four-outcome polarization measurement on V and A and then sends one of four messages (two bits) to Bob.

Alice never finds out the quantum state of V, the message doesn't reveal it, and V's initial quantum state is destroyed by the game.

Victor runs over to Bob and finds that B now has the same quantum state as V had.

What's strange about the behavior of quantum systems?

Entanglement
Quantum correlations

We cannot account for quantum teleportation in terms of the photons' having pre-existing polarizations that are discovered by the measurements.

But we haven't shown that yet. Everything so far can be explained in terms of two 1-bit coins (for X and Y polarizations). But to teleport all polarization, not just X and Y, Alice needs to communicate only two bits to Bob; the correlations of all these coins are too strong be explained in terms of coins with pre-existing properties.

Claret cup cacti
New Mexico

Quantum entanglement can be used for useful tasks such as teleportation of quantum states.

Greenberger-Horne-Zeilinger (GHZ) entanglement

3-qubit GHZ entangled state: $\frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$

qubit

x	y
X	Y

1st qubit

x_1	y_1
X	Y

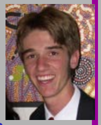
2nd qubit

x_2	y_2
X	Y

3rd qubit

x_3	y_3
X	Y

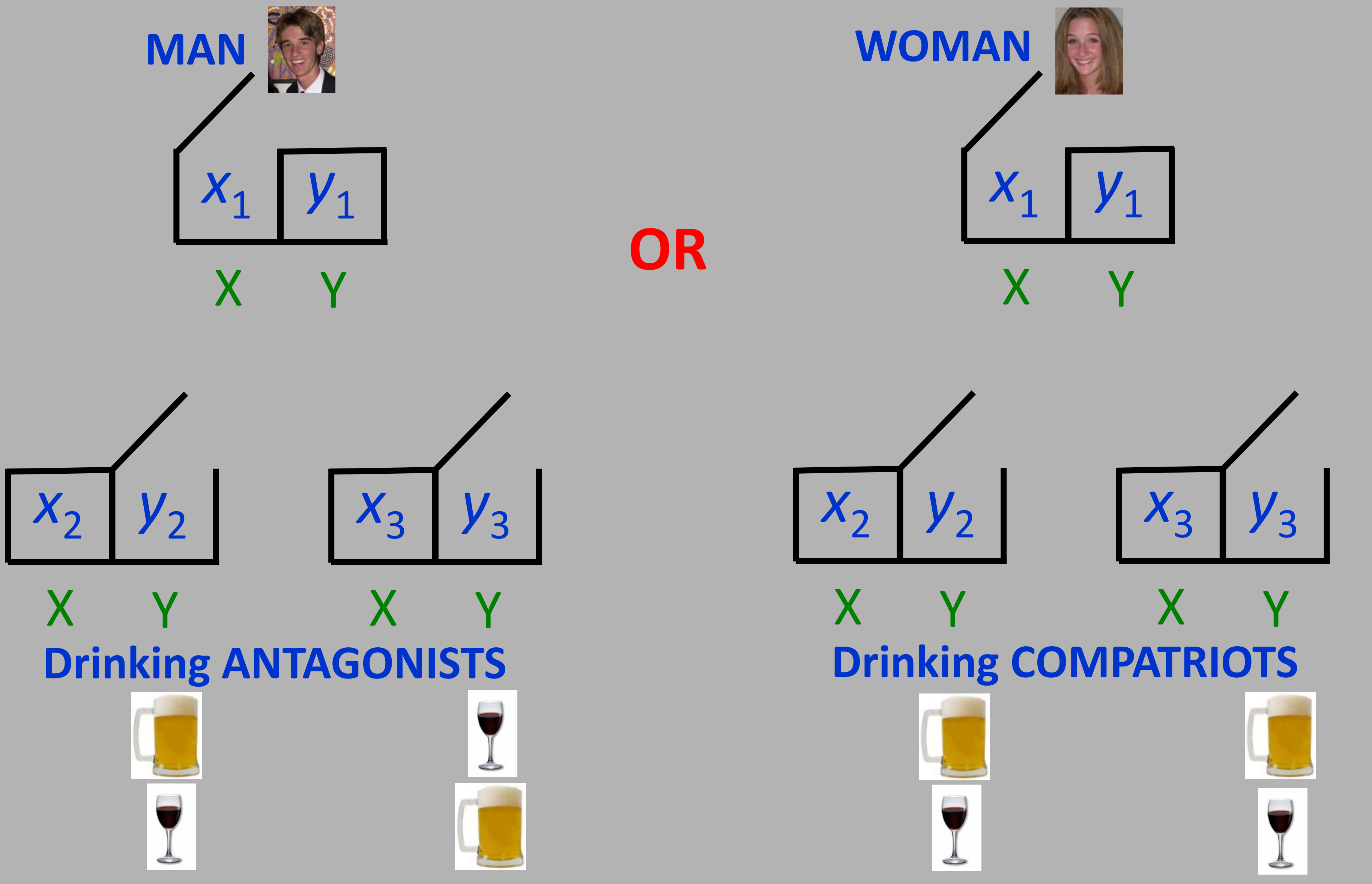
Let's tell a story: a qubit becomes a two-bit person

x=0 (heads) is a MAN. 

x=1 (tails) is a WOMAN. 

y=0 (heads) drinks BEER. 

y=1 (tails) drinks WINE. 



Ask one person for gender, the other two for drinking preference.

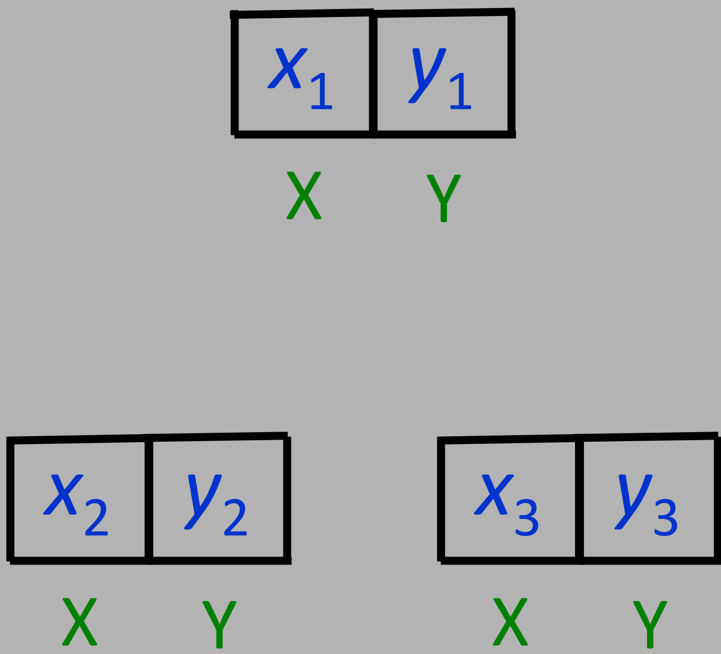
2 heads and 1 tail or 3 tails

2 zeroes and 1 one or 3 ones

$x_1 + y_2 + y_3$ is odd.

Summarize

Ask one person for gender, the other two for drinking preference.



2 heads and 1 tail or 3 tails

2 zeroes and 1 one or 3 ones

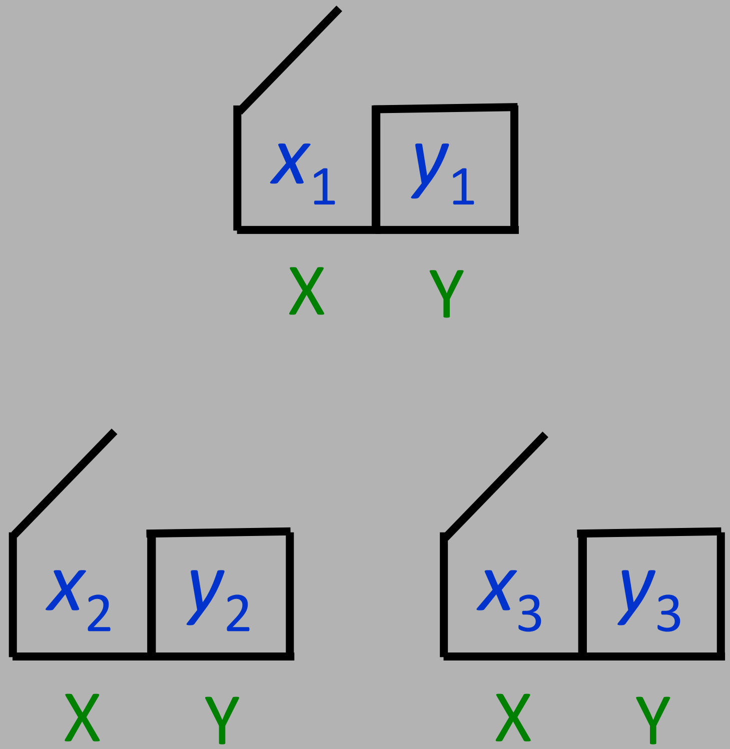
$x_1 + y_2 + y_3$ is odd.

$y_1 + x_2 + y_3$ is odd.

$y_1 + y_2 + x_3$ is odd.

A MAN is always accompanied by two ANTAGONISTS.

A WOMAN is always accompanied by two COMPATRIOTS.



Ask one person for gender, the other two for drinking preference.

2 heads and 1 tail or 3 tails

2 zeroes and 1 one or 3 ones

$x_1 + y_2 + y_3$ is odd.

$y_1 + x_2 + y_3$ is odd.

$y_1 + y_2 + x_3$ is odd.

Now ask all three persons for gender.

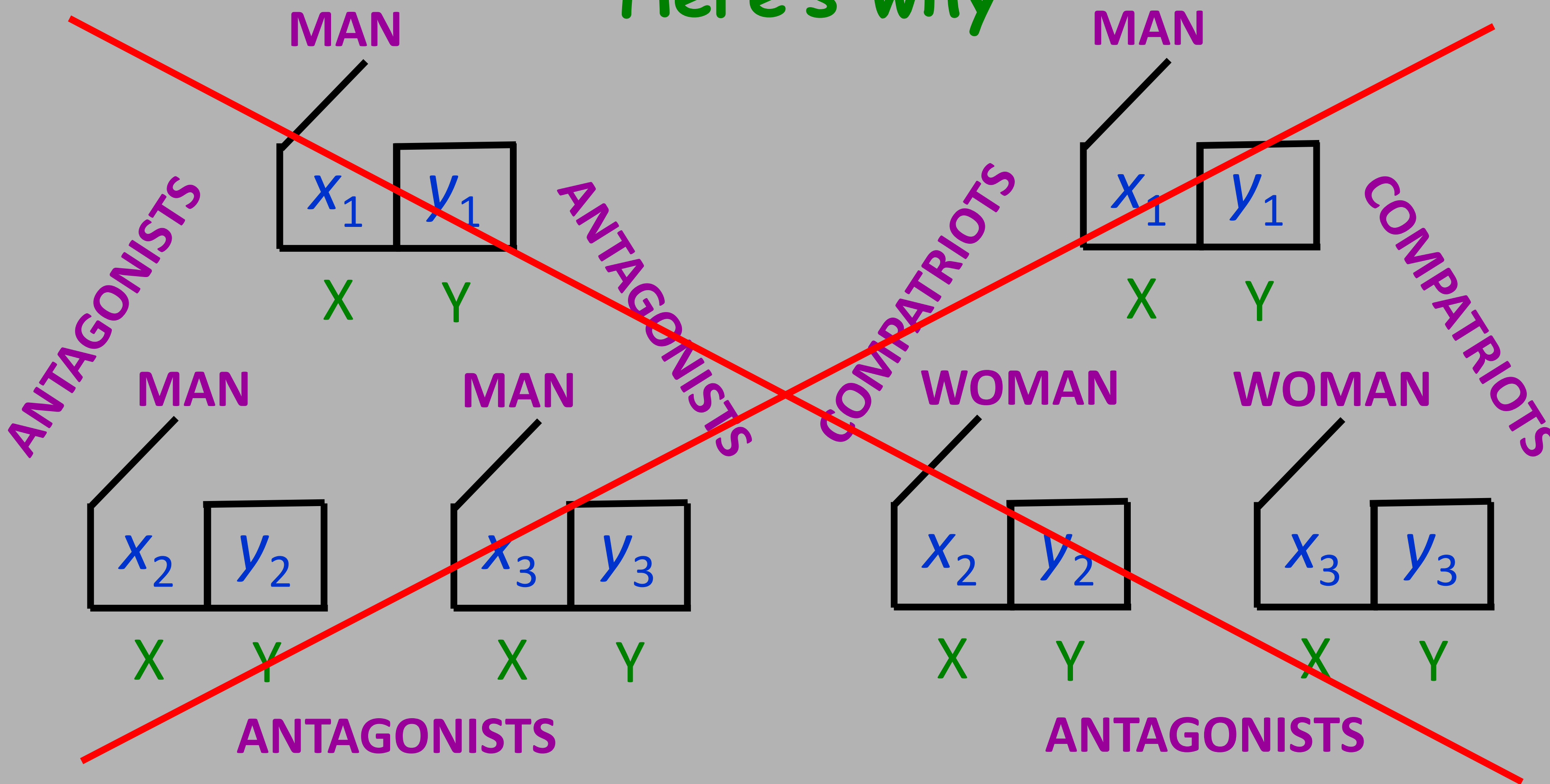
2 heads and 1 tail or 3 tails

2 zeroes and 1 one or 3 ones

$x_1 + x_2 + x_3$ is odd.

There must be two MEN and a WOMAN or three WOMEN.

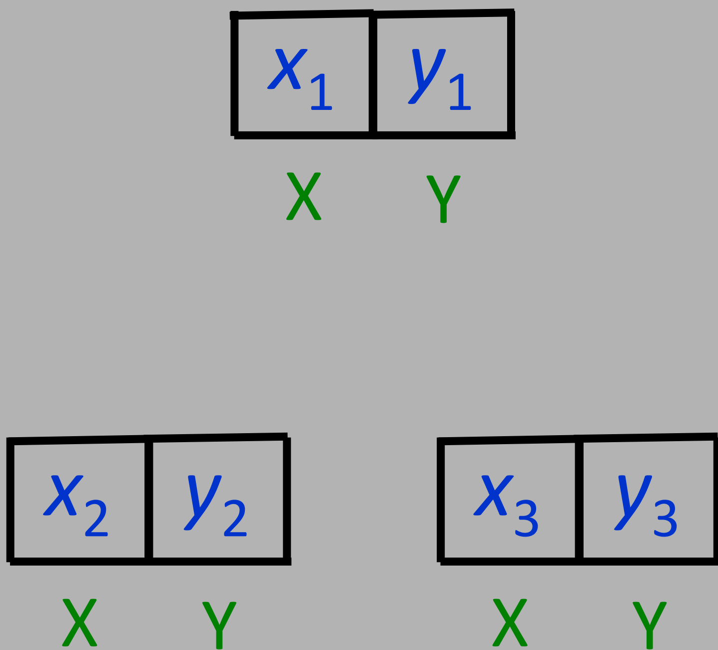
Here's why



A MAN is always accompanied by two ANTAGONISTS.
A WOMAN is always accompanied by two COMPATRIOTS.

There must be two MEN and a WOMAN or three WOMEN.

Quantum mechanics: only what we just showed to be impossible occurs.



2 heads and 1 tail or 3 tails
2 zeroes and 1 one or 3 ones

$x_1 + y_2 + y_3$ is odd.
$y_1 + x_2 + y_3$ is odd.
$y_1 + y_2 + x_3$ is odd.

~~**2 heads and 1 tail or 3 tails**~~
~~**2 zeroes and 1 one or 3 ones**~~
~~$x_1 + x_2 + x_3$ is odd.~~

2 tails and 1 head or 3 heads
2 ones and 1 zero or 3 zeroes

$x_1 + x_2 + x_3$ is even.

A MAN is always accompanied by two ANTAGONISTS.
A WOMAN is always accompanied by two COMPATRIOTS.

~~**There must be two MEN and a WOMAN or three WOMEN.**~~

There must be two WOMEN and a MAN or three MEN.

What's strange about the behavior of quantum systems?

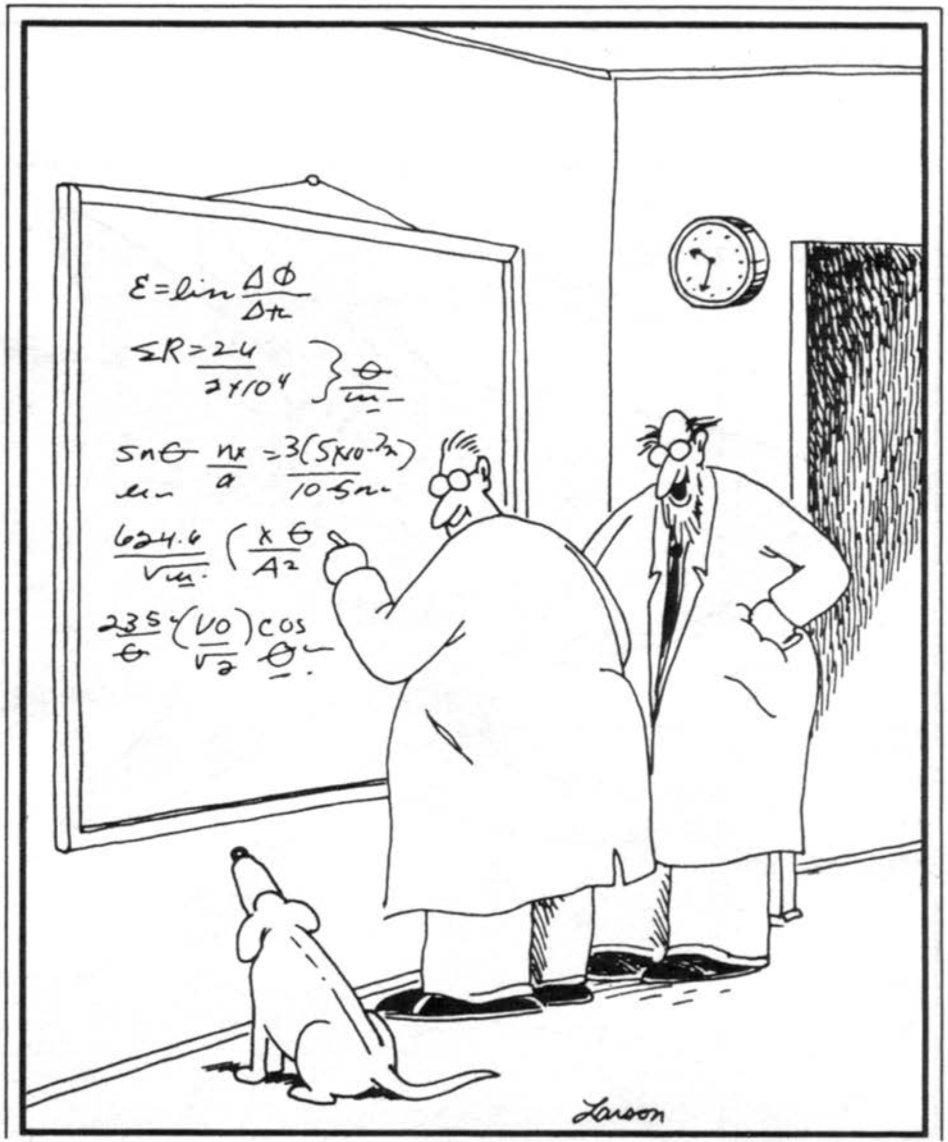
Entanglement
Quantum correlations
Correlations—even perfect correlations— that violate the rules of ordinary existence.

We cannot account for the behavior of quantum systems by imagining that properties have pre-existing values that are discovered by observation.

Bungle Bungle Range
Western Australia

Objects in the world of the very small violate the rules of ordinary existence: either they are not individual objects, or they do not have realistic properties. The result is magic.

It's not only dogs that can't understand quantum mechanics.



"Ohhhhhh…Look at that, Schuster…Dogs are so cute when they try to comprehend quantum mechanics."

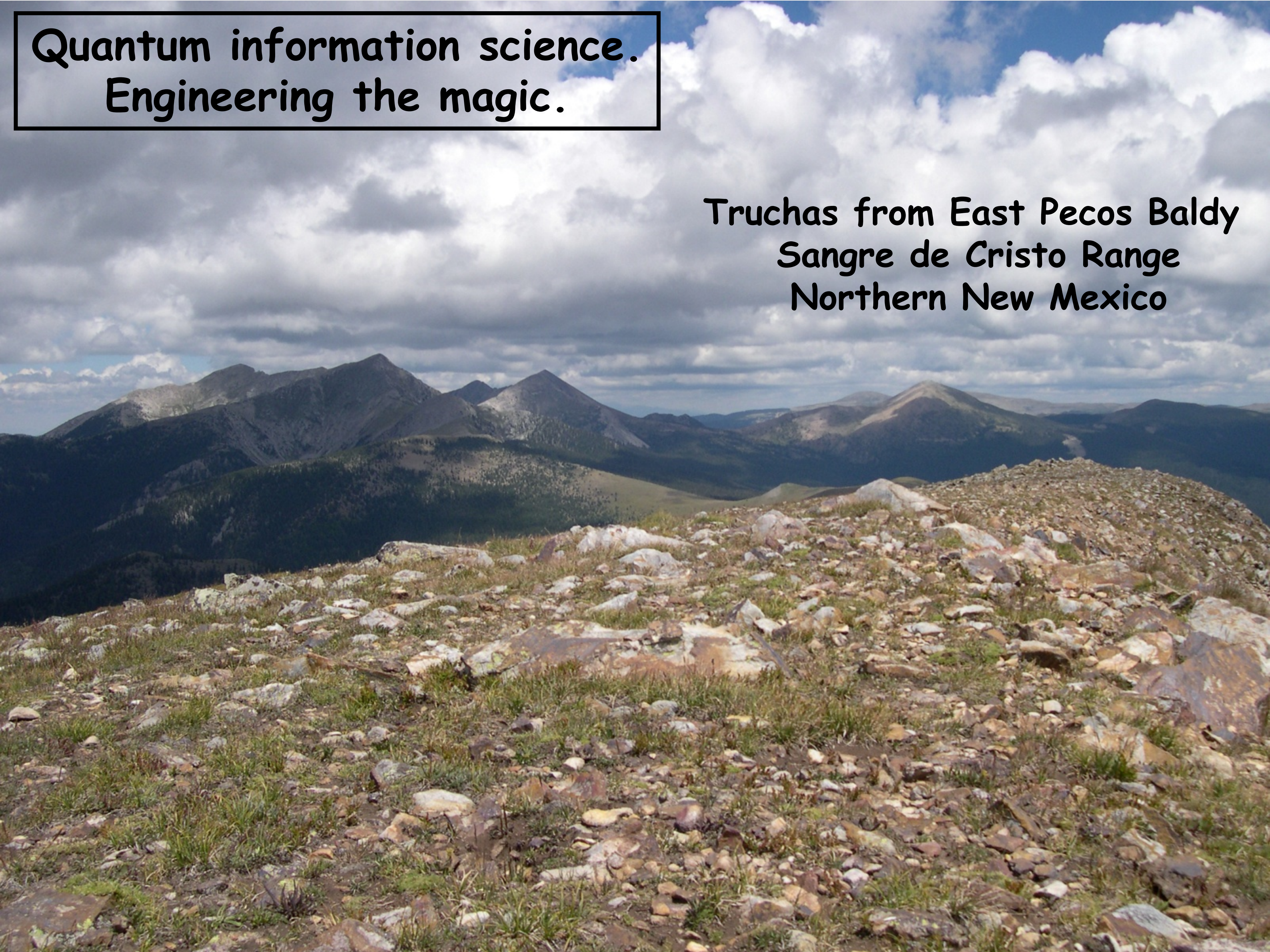
Quantum physics leads you to a world of magic, beyond your imagination, but provides a set of rules to manage and control the magic.

Quantum information science is the discipline that explores information processing within the quantum world, where the mundane constraints of realism and determinism no longer apply.

Why not extend the magic into the world of the everyday?

The more magic you attempt, the harder it gets.

Quantum information science. Engineering the magic.



Truchas from East Pecos Baldy
Sangre de Cristo Range
Northern New Mexico

Private communication

Alice and Bob share a *one-time pad* (secret random key).

	H E L P	
	00111 00100 01011 01111	Message
⊕	01110010011010010011	Key (random string)
	01001011011111111100	Coded message
⊕	01110010011010010011	Key (random string)
	00111001000101101111	Message

But where do Alice and Bob get the key?

Quantum key distribution using entanglement

Alice

Alice measures X, Y, U, or V polarization.

Photon A

Bell entangled quantum state

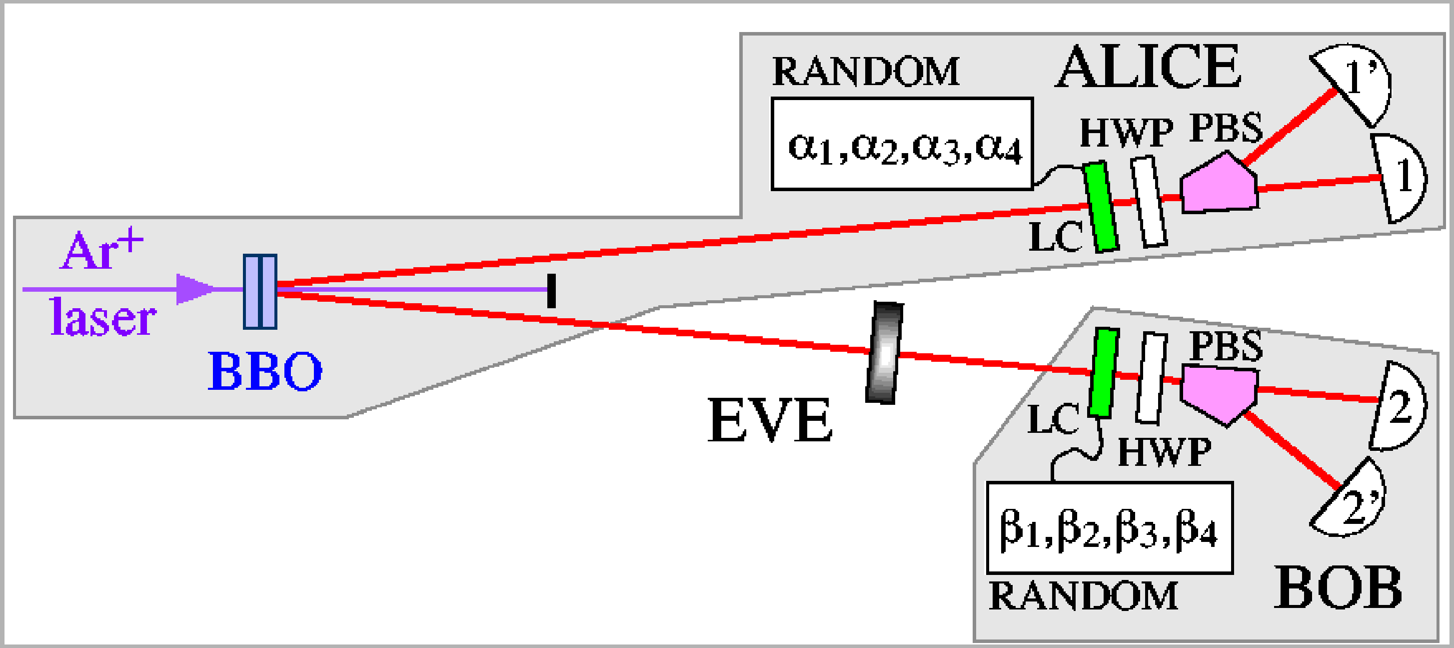
Photon B

Alice and Bob share the *type* of measurement they did, not the result. If they measured the same thing, they keep the shared random bit for their key. Otherwise, they use the results to verify a *Bell inequality*, which can be used to rule out the presence of an eavesdropper.

Bob

Bob measures X, Y, U, or V polarization.

Quantum key distribution using entanglement



Experiment at Los Alamos National Laboratory (2000): D. S. Naik, C. G. Peterson, A. G. White, A. J. Berglund, and P. G. Kwiat

Why is quantum key distribution secure?

An unmeasured qubit has no bit value waiting to be discovered. Alice and Bob create the key by measuring the polarizations. Before that, there is no key for an eavesdropper to steal.

"There is no there there."
Gertrude Stein damning her native Oakland and inadvertently describing quantum systems.

Essential ingredient: Entanglement between qubits